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Spatial and Temporal Patterns of Lobster Trap Fishing: A Survey of Fishing Effort and Habitat Structure

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Abstract.—The patterns of distribution and abundance for the California spiny lobster (*Panulirus interruptus*) within the kelp forest off La Jolla, CA (USA) were compared to the distribution of fishing effort during the 2005/2006 lobster season over an area of ~20.25 km^2. Fishing intensity was greatest at the beginning of the season (3333 traps on opening day) decreasing to 258 traps a few days before the end of the 24 week-long season. The collective effort of the trap fishermen primarily targeted the best habitats at the scale of the kelp forest, but fishing effort at smaller scales (250m, the smallest scale of our study) was less correlated to the best lobster habitats, especially near the beginning of the season. Fishing efficiency (CPUE) decreased linearly throughout the season, decreasing by more than an order of magnitude despite the fact that the distribution of fishing effort was better correlated with habitat quality and distribution near the end of the season. Fishing effort was greatest throughout the season at the edge of a small no-take marine protected area indicating possible fishing of spillover.

Successful commercial fishermen base their effort on knowledge that can transcend generations of observation and experience. Their knowledge accrues over relatively large areas and over long temporal periods that allow the fishermen to adjust their effort to all sorts of environmental contingencies. Ecologists and fishermen share an interest in roughly the same questions about resources, but ecologists are traditionally constrained to relatively small scales in time and space. It is important to incorporate the experiential knowledge of fishermen into the body of knowledge developed by scientists. Spatial information can be the means to a common language for communicating fishermen's knowledge to the scientific and management community and vice versa.

This paper compares the fishing effort of lobster fishermen working in the La Jolla kelp forest with a scientific study of the habitat. Specifically, we investigate the relationship between the benthic structure of the fishing ground and the spatial and temporal distribution of fishing effort on spiny lobster (*Panulirus interruptus*). We seek to describe the fishing effort and understand this effort as the result of the collective behavior of several fishermen fishing with different intensity and experience. Such a constructive interaction has developed for the American lobster fishery in New England (Steneck & Wilson 2001).

Methods

The seafloor off La Jolla (Fig. 1) provides a large suitable habitat for spiny lobsters that supports an important fishery. The habitat off La Jolla includes shal-

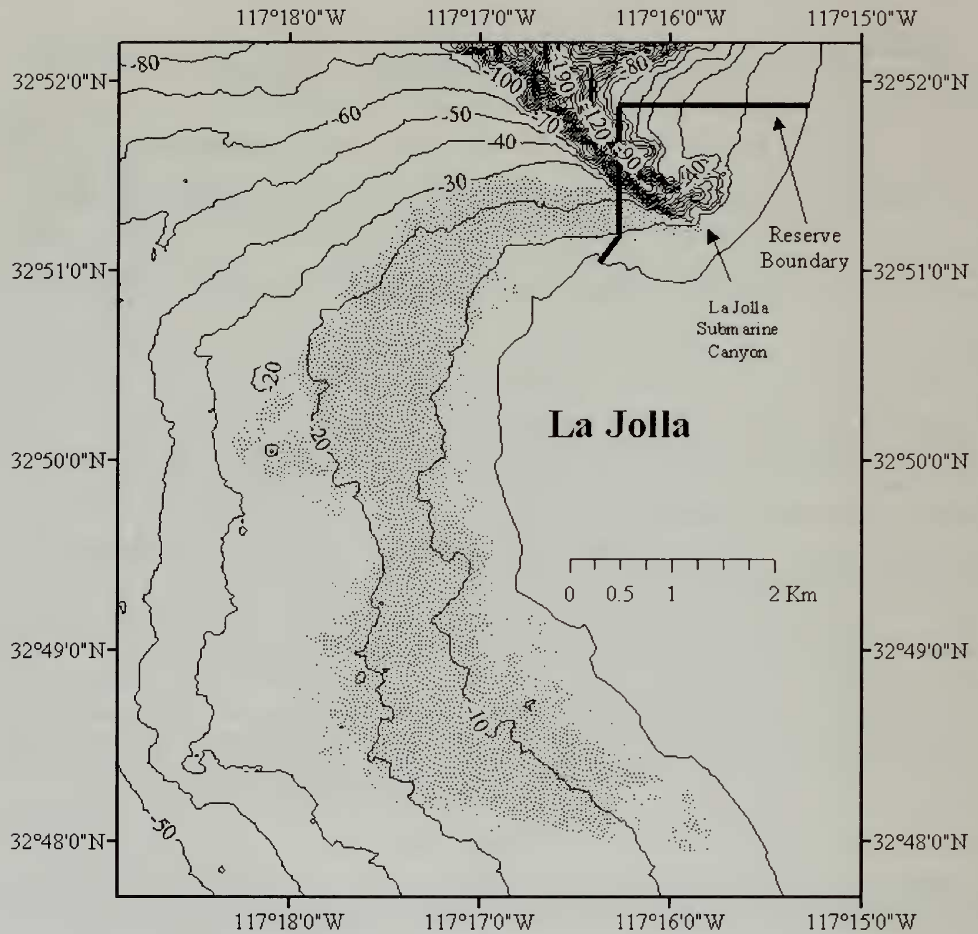

Fig. 1. Map of the seafloor off La Jolla indicating the locations of the La Jolla kelp forest (stippled area) and the San Diego-La Jolla Ecological Reserve. The northernmost portion of the kelp forest and the head of the La Jolla Submarine Canyon are protected within this Reserve. Depth contour units are contours.

low surf grass beds, shallow rocky habitat with a high degree of vertical structure and crevices, and deeper rocky habitat characterized by boulder and outcrop reefs, ledge and crevice systems and boulder and rock fields. The area also supports the second largest kelp forest off California and includes the San Diego-La Jolla Ecological Reserve. The reserve is a 'no-take' marine reserve established in 1971 to protect the southern margin of La Jolla Bay where several types of habitats are found including kelp forest habitat, shallow boulder-reef habitat, sloping sandy shelf habitat, and the head of the La Jolla Submarine Canyon.

The distribution of fine-scale habitats within the La Jolla kelp forest and the affinity of twenty exploited species (including spiny lobsters) to these habitats was determined as part of a different study (see Parnell et al. 2005; Parnell et al. 2006). The habitat survey was stratified using a grid system in which boxes were 250 m on a side (this scale was derived from a pilot study of the spatial scale of habitat variability off La Jolla). Habitat parameters, fish and invertebrates were

Table 1. Primary and secondary characteristics of habitat types within the La Jolla kelp forest and the fractional affinity of spiny lobster to each habitat. Primary habitat characteristics are the characteristics that were the greatest within that particular habitat, and secondary characteristics are those whose values were >75% of the value for the habitat where each characteristic was greatest.

Habitat	Primary Characteristics	Secondary Characteristics	Lobster Affinity
RTR	reefs, *Eisenia arboria, Cystoseira osmundacea,* red turf algae, articulated coralline algae	sand, var(depth), relief, ledges, crevices, overhangs, *Laminaria farlowii*	0.347
RSUR	bedrock, rock, var(depth), relief, overhangs, *Agarum fimbriatum, Desmerestia ligulata,* brown turf algae	reefs, crevices	0.310
CanG	crevices, *Macrocystis pyrifera,* crustose corraline algae	bedrock, bedrock with sand, ledges	0.216
UG	bedrock with sand, ledges, *Pterygophora, californica, Laminaria farlowii*	*Desmerestia ligulata,* articulated coralline algae	0.095
CobG	cobble, sand	*Pterygophora californica*	0.068

surveyed along randomly-placed 30m band transects within the stratified grid system. Each box within the grid was targeted randomly and several (4–12) transects were surveyed within each box. Habitat parameters including depth variability (var(depth)), vertical relief, bottom substrate, bottom features (reefs, crevices, ledges, and overhangs), and algal guilds were analyzed using divisive clustering analysis. Five robust nominal habitats, determined by resampling the data, were discriminated using this approach. The affinity of lobsters to these habitats was determined from lobster densities estimated from counts along the habitat transects. The proportional affinity of spiny lobster (proportion of lobsters surveyed within a particular habitat type throughout La Jolla) varied significantly among the habitats. The five habitats were named for unique characteristics: "red turf reefs" (RTR), "red sea urchin reefs" (RSUR), "canopy gardens" (CanG), "understory gardens" (UG), and "cobble gardens" (CobG). The primary characteristics of these habitats and the proportional affinity of lobsters (fraction of lobsters surveyed within a particular type of habitat throughout La Jolla) to these habitats are listed in Table 1. Knowledge of how these habitats are distributed within La Jolla and their importance to spiny lobster provides a framework with which to compare the distribution of commercial fishing effort for lobsters.

Lobster trap floats were visually counted throughout La Jolla from the 4m to the 33m depth contours (an area of ~20.3 km^2) during the 2005/2006 lobster season. Lobster trap floats reflect the location of lobster traps on the bottom because the floats are attached to traps by lines having minimal scope to minimize trap loss due to fouling or propeller damage. Floats were visually counted within a grid composed of boxes 250 m on a side that corresponded exactly to the grid system used for the habitat study. Floats were surveyed four times throughout the season − 5 Oct (opening day; T1), 26 Oct (T2), 11 Jan (T3), and 15 Mar (T4). Sampling days were chosen to avoid stormy periods. The lobster season of 2005/2006 opened to commercial fishing on 5 Oct, 2005 and closed on 22 Mar, 2006. Lobster traps were repeatedly surveyed over the course of the lobster season to gauge whether lobster fishermen collectively targeted different habitats with different intensities as the season progressed.

We tested the spatial distribution of traps on all sampling days by dividing the variance by the mean (Index of Dispersion). Values for all days were substantially larger than 1 (see Results) indicating traps were contagiously distributed (c.f., clumped). Frequency distributions of traps (on all days and their average distribution) were then statistically compared to a negative binomial distribution using chi-square tests to determine if the spatial distributions of traps were significantly contagious.

The relationship of fishing effort among days was determined by calculation of a correlation matrix of traps in their respective boxes among the days that the survey was conducted. The observed spatial distribution of traps was observed to be depth-dependant with more traps closer to shore. Therefore the number of traps observed in each box was also correlated with the average depth within each corresponding box. All correlations were performed using S-Plus, a statistical program.

The distribution of fishing effort was then related to habitat distribution by correlating the number of traps observed in each box with lobster habitat affinities (from the band transect surveys) within the same area at ever increasing spatial scales. This technique estimates the degree of correspondence between fishing effort and the value of the habitat for lobster over a range of spatial scales. A smaller spatial scale of correspondence implies that fishing effort is better focused on good lobster habitat. A Matlab script file was written to correlate the number of traps to lobster habitat affinity using moving-window averaging (simple averaging). Window sizes within the correlation analysis ranged from 1 box to 64 boxes, roughly half the size of the kelp forest. We assume that areas having the highest habitat affinities are likely the most productive areas to fish simply because they contain more lobsters. P-values of the corresponding correlation coefficients were computed within Matlab (t-statistic having n-2 degrees of freedom).

Lobster catch data (monthly catch data for La Jolla; California Department of Fish and Game block 0842—the block covering the La Jolla kelp forest) for the 2005/2006 season was used to estimate the catch per unit effort for the days that traps were counted. Monthly catch data were divided by the number of lobster fishing days for each month to standardize monthly catch rates to daily rates. A second order regression of standardized daily catch rate as a function of days since the beginning of the season was calculated using S-Plus to estimate daily catch rates for the days that traps were counted. The second order regression of daily catch rates as a function of seasonal day was significant ($p<0.001$; $r^2 = 0.954$).

Results

Fishing intensity decreased as the season progressed (Table 2) from a high of 3333 traps on opening day to only 258 traps near the end of the season. The distribution of traps for each day is shown in Figure 2. Trap distributions varied among days and with depth (Fig. 3). Traps were shallowest on opening day (T1) and near the end of the season (T4). The distribution of traps was deepest and spread over a larger depth range on T3.

For all days, trap distributions were not significantly different from the negative binomial distribution ($p>0.05$). Therefore, traps were significantly distributed in

Table 2. Summary statistics for the days that traps were surveyed.

Date	Total Traps	Traps Box^{-1} Mean	Traps Box^{-1} S. Error	Index of Dispersion
5 Oct, 2005	3333	10.25	0.53	8.8
26 Oct, 2005	1837	5.65	0.25	3.5
11 Jan, 2006	553	1.70	0.14	3.7
15 Mar, 2006	258	0.79	0.07	2.1

a clumped distribution. Trap distributions for each day of the survey is shown in Fig. 3. Note that there were more traps in northern La Jolla, and that the most heavily fished boxes were in shallow habitat adjacent to the reserve.

The most obvious pattern in the data was the distribution of lobster traps with depth. The correlation of traps (see Table 1) with depth was significant for T1 ($p \cong 0$, $R^2 = 0.48$), T2 ($p \cong 0$, $R^2 = 0.38$), and T4 ($p \cong 0$, $R^2 = 0.21$), but not for T3 ($p = 0.80$). The distribution of fishing effort was significantly correlated among days (Table 3). Fishing patterns were the most similar on the first two

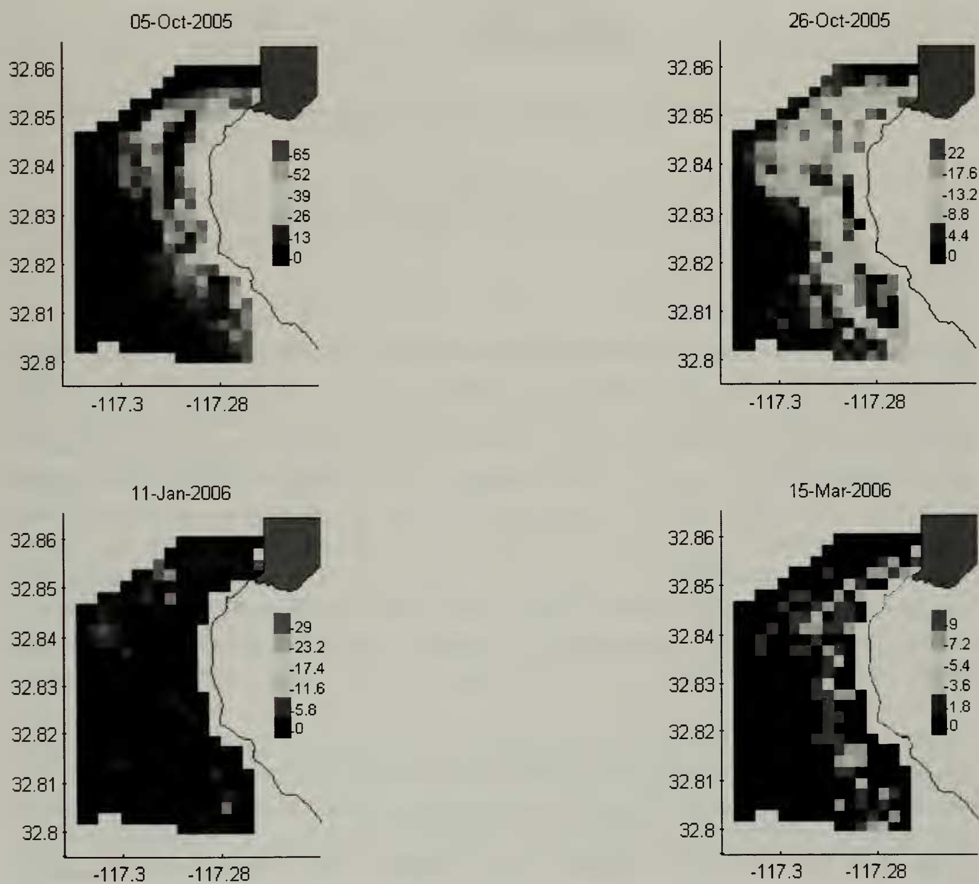

Fig. 2. Traps distributions on all sampling days. Colors indicate the number of traps observed in each sampling box. Note the colorbar scale is different among days. The San Diego-La Jolla Ecological Reserve is shown in grey.

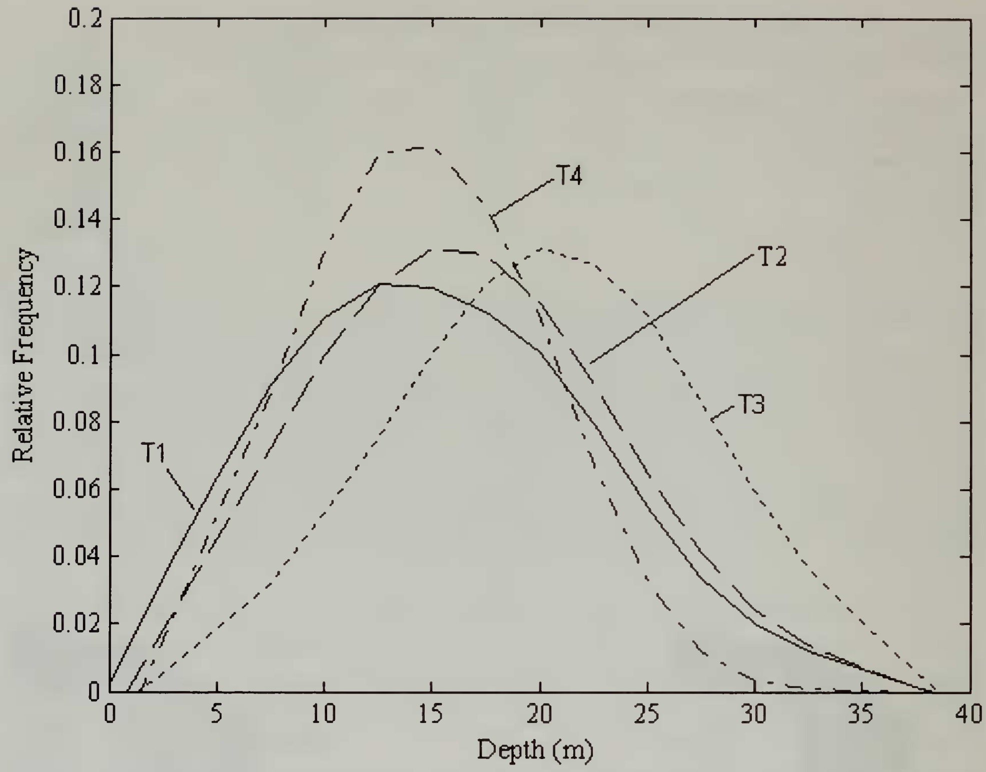

Fig. 3. Relative frequency distribution of lobster traps with depth for each day that lobster traps were surveyed (T1 = opening day of season, 5 Oct 2005; T2 = 26 Oct 20005; T3 = 11 Jan 2006; T4 = 15 Mar 2006).

days of sampling. The distribution of traps on T3 was the most different among the days but was still significantly correlated.

The distribution of habitat value for lobster, derived from SCUBA survey data, is shown in Figure 4. Habitat values are relative to the best-observed habitat for spiny lobsters within the kelp forest. Habitat values for each box were computed as average of habitat affinity among band transects conducted within each box. Kelp forest habitat extends into the Reserve in an area approximately the size of one box and is located next to the western boundary. The habitat within this area is mostly composed of "red turf reefs", which has the highest lobster affinity.

The results of the moving window correlation analysis of fishing effort distribution and habitat affinity are shown in Figure 5. The distribution of fishing effort

Table 3. Matrix of correlation coefficients of trap distributions among days and average box depth. All correlations are significant ($p<0.05$) except for the correlation of T3 with depth.

	Depth	T1	T2	T3	T4
Depth	—	−0.6944	−0.6216	0.0137	−0.4542
T1		—	0.5110	0.2808	0.3477
T2			—	0.2915	0.3827
T3				—	0.4328

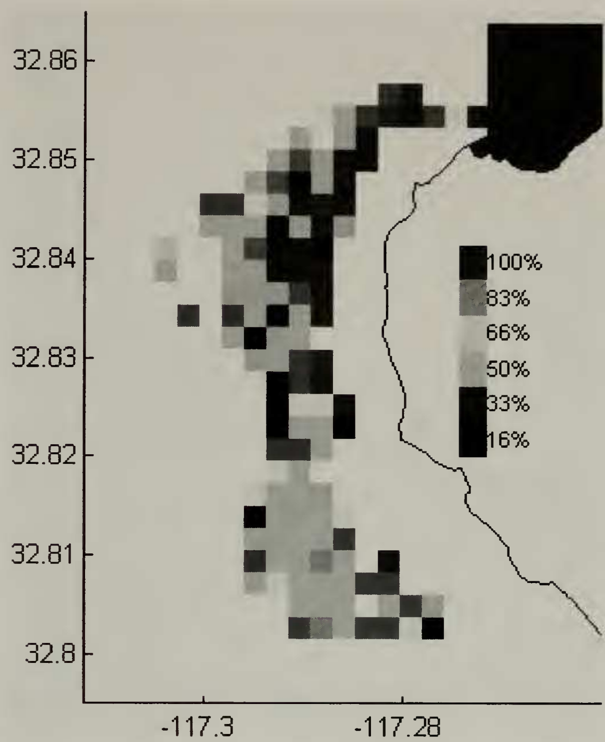

Fig. 4. Distribution of habitat value for lobster within the kelp forest. Colors denote value of habitat to lobster (affinity) relative to the habitat having the highest value (100%).

on T1, T2, and T3 were not closely related at the smaller scales (<~20 boxes) but were closely related at larger scales. Whereas, fishing effort on T4 was more closely related to habitat distributions at smaller scales. Correlations were significant ($p<0.05$) for window sizes greater than 9 boxes for T1, 10 boxes for T2, 12 boxes for T3, and for all window sizes for T4.

Catch per unit effort appeared to decline linearly throughout the season (Fig. 6) and was very low by the end of the season.

Discussion

Our motivation was to evaluate the coupling between fishing patterns in time and space with quantitative scientific determinations of habitat distribution and quality. Fishing patterns for spiny lobster off southern California result from the collective behavior of several independent fishermen with various levels of experience and motivation. The fleet is composed both of very experienced fishermen who have spent their lives in the business and who were taught by previous generations of experienced fishermen, and of less experienced fishermen who are learning their trade. When the season opens, fishermen compete to catch as many legal-sized lobsters as quickly as possible before they are locally depleted. Current management practices limits only the number of fishing permits, not the level of effort expended by each license holder. The spiny lobster fishery off California appears saturated with fishermen as evidenced by the historical reduction in size distributions of lobsters beginning as early as the turn of the last century (Allen

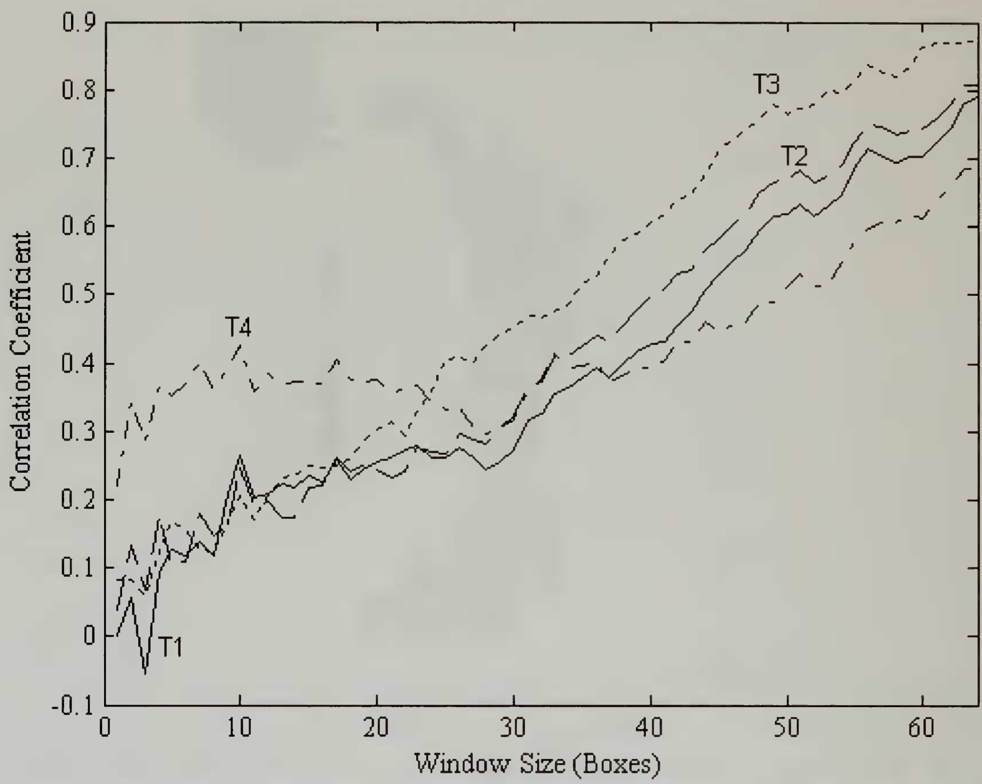

Fig. 5. Results of moving window correlation analysis of habitat value (c.f., affinity) and the distribution of fishing effort. Each curve represents a sampling day. Correlation coefficients were calculated between moving averages of habitat affinity and trap distribution at ever increasing window sizes. Each curve represents one day of the survey.

1913, CDFG 2001). Fishing intensity is dictated by the competition among fishermen as they rush to catch most of the lobsters that have grown to legal size since the previous season. Commercial fishing has been shown to profoundly affect size distributions, fecundity and sex ratio (Iacchei et al. 2005). However, management of the fishery—primarily composed of restricted access permits, size limits, and trap-design rules—appears to be successful. Lobster catch, while fluctuating with the dynamic ocean climate off California, appears stable over the long term. Current management practices were developed in a collaborative effort between the California Department of Fish and Game and the commercial trappers.

The primary results of this study (1) document fishing intensity over time in which the number of traps decreased precipitously from 3333 on opening day to 258 traps remaining just a few days prior to the end of the season, (2) confirm that the collective effort of the fishermen is primarily directed at the better habitats at the scale of the kelp forest but not always at finer spatial scales, (3) indicate that, despite the rapid decline in fishing effort, fishing efficiency (CPUE) decreases throughout the season and is very low by the end of the season, and (4) document a disproportionate fishing effort throughout the season near the edge of the San Diego-La Jolla Ecological Reserve.

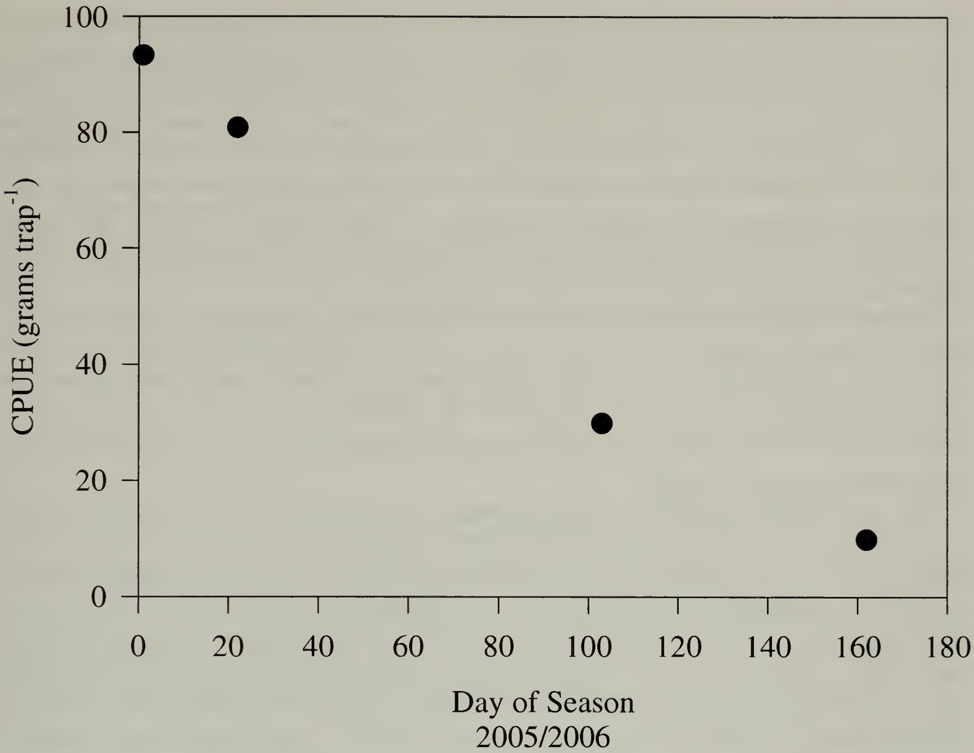

Fig. 6. Lobster CPUE (daily catch modeled using a second order regression from monthly catch data; see methods) plotted against day of the season. Catch data are courtesy of Joann Eres and Jana Robertson of the California Department of Fish and Game.

The fishing strategies of fishermen result from a combination of factors (e.g., see Bene & Tewfik 2001). These include the historical knowledge that accrues across generations about ocean conditions and stock behavior, stock condition, market conditions, risk management, and the cost of fishing. For lobster fishermen in southern California, the primary fishing pattern is to fish shallow in the beginning of the season to exploit the best shallow habitats before the winter storm season arrives and before some portion of the stock (this is not well documented at present) moves into deeper waters during the winter months. The distribution of effort we observed was shallow and intense early in the season, followed by less intense fishing distributed further offshore and across a wider depth zone by mid-season, and a highly focused but greatly decreased effort in shallow waters by the end of the season.

Early in the season there were so many traps that it was impossible to discriminate fishing effort among individual fishermen (floats are painted with distinctive patterns for each fisherman), but by the end of the season it was apparent that nine different fishermen were still fishing and their effort was mostly spread over areas consisting of no more than six of our sampling boxes. The spatial distribution of fishing effort for these nine fishermen best matched our fine-scale habitats. Thus, we assume that these fishermen were highly experienced and knowledgeable. Earlier in the season there was likely a greater mix of experience and knowledge among the fishermen and therefore greater discrepancies between the habitats and fishing effort. Fishermen were still distributing their traps wisely at the scale of the kelp forest, targeting the shallower and northern areas of La Jolla, however, their fishing effort was much less focused on the fine-scale habitats diluting their effort by as much as 400–600 m based on the correlation analysis. This is much greater than the distance lobsters are known to move when they are either home denning (an aggregate working a home range of not greater than ~100 m), or when they are nomadically denning (the aggregate moving farther but still not greater than about 350 m; Stull 1991).

Fishing efficiency decreased throughout the season despite our results that indicate fishermen targeted the most appropriate fine-scale habitats near the end of the season. This suggests that there were few legal lobsters off La Jolla by the end of the season. The effort expended by fishermen is therefore adequate to remove most of the legal-sized lobsters before the end of the season assuming all legal lobsters can be caught.

The last important pattern is that fishing is concentrated near the western edge of the Reserve. This area has good lobster habitat (as defined in Parnell et al. 2006), but it is still fished disproportionately higher than similar habitat further south. This suggests that the fishermen are targeting spillover from the reserve. This argument is further supported by the fact that fishermen are concentrating their traps near the Reserve proportionately more during the middle and latter stages of the season suggesting that most of the legal-sized lobster left by the end of the season are those moving out of the Reserve. Traps were also observed immediately north of the northern boundary of the Reserve during the latter half of the season. This entire area is a sandy shelf and devoid of lobster habitat and therefore was not surveyed for traps. However, the presence of traps in such poor habitat during the latter part of the season, and not near the beginning, further suggests that the fishermen are fishing spillover from the Reserve.

Finally, we advocate that ecologists develop better relationships with the experienced fishermen (e.g., Steneck & Wilson 2001) because the fishermen's experience has provided them with a sophisticated understanding of the behavior of the animals that they exploit, and ecologists have much to learn from them.

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